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# Large Plate Lysimeter Efficiency for Collecting Water Transported from Soil to Ground Water

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# Large Plate Lysimeter Efficiency for Collecting Water Transported from Soil to Ground Water

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**Abstract**

A large, zero-tension, plate lysimeter (3.05 x 2.13 m) was installed to intercept percolating soil water at Bikini Atoll ($11^0$ 35'N, $165^0$ 25'E), a former nuclear test-site. In two experiments controlled amounts of irrigation water were applied over the lysimeter and leachate water was collected. Evapotranspiration (ET) calculations were made using the Penman-Monteith equation and climate data collected at the atoll. The efficiency of the lysimeter was essentially 100% in contrast to low efficiencies reported for smaller plate lysimeters. Lysimeter design, installation, and water-balance results are discussed.

## Background

Plate lysimeters, generally flat rectangular "plates" made of various types of metal, have for many years been inserted into the soil below the surface to collect water percolating downward in the soil. Development of very large, zero-tension plate lysimeters was required to improve efficiency and collect sufficient water to measure $^{137}$Cs concentration in percolating fresh water transported to the ground-water lens at Bikini Island. With such data, the rate of removal of $^{137}$Cs from soil could be determined.

Low collection efficiency of small zero-tension plate lysimeters has long been known (Kohnke et al., 1940). Plate lysimeters of 162 cm$^2$ (5.4 x 30 cm) produced collection efficiencies of only 10% (Russell and Ewel, 1985). Radulovitch and Sollins (1987) found greater collection efficiency as plate lysimeter size increased from 162 to 500 to 2500 cm$^2$ (50 x 50 cm) with efficiencies of 10%, 13%, and 26-36%, respectively. Zhu et al., (2002) increased plate size to 4636 cm$^2$ (76 x 61 cm) that gave a collection efficiency of 25% but this size lysimeter is still very small and collection efficiencies are much lower than for wick lysimeters (Louie et al., 2000; Zhu et al., 2002). Water tension border effects are an issue with small lysimeters as discussed by Boll et al., (1991) and Jemison and Fox (1992).

Plate lysimeter efficiency calculations should account for loss of precipitation water by ET over the time-period of study. Zhu et al., (2002) define leachate collection efficiency (LCE) as "collected leachate water divided by the sum of precipitation water plus irrigation water minus the ET water". Mean annual LCE was 48% (range 34 to 61%) for 18 lysimeters. Jemison and Fox (1992), using the same lysimeters, estimated an efficiency of 52% (range 13-92%).

We explored the utility of very large, tilted, zero-tension plate lysimeters because (1) literature data indicate an increase in collection efficiency with increase in size of zero-tension plate lysimeters (2) the tension system of silt- and clay-free porous sands was unusually favorable, (3) prospects of using plates large enough to reduce the soil water tension border effects and spatial variability, and (4) an ability to insert large plates in a ~25 year coconut grove without disturbing surface soil and most of the root system.

## Materials and Methods

Atoll soils are Typic Rendolls formed on water-deposited sand that is almost exclusively composed of coral, shell, and calcareous algae with essentially no mineral clay. Lysimeter-site sands contain only ~2% particles greater than 2 mm, 43% between 2 mm and 0.5 mm, and 55% finer than 0.5 mm. A very small percentage is finer than 0.1 mm. Abraded tests of a foram, *Calcarina sprengleri,* make up a large proportion of very coarse sand. Surface soil is commonly 20 to 25 cm deep with a bulk density between 0.9 and 1.1 g $cm^{-3}$, organic content ranging from 3 to 15% based on a loss on ignition at @430° C (Robison and Stone, 1992), and a field water capacity (FWC) (w/w) ranging from 22 to 28% (Stone and Robison[1]). Organic content diminishes with depth from 25 to 50 cm. Below 50 cm there is essentially no organic matter and the white sand bulk density is 1.2 to 1.3 g $cm^{-3}$ with 12 to 13% FWC.

Water flow from soil surface to depth is vertical with essentially no lateral flow and often there are no impermeable or hardened horizons between the surface and groundwater lens to divert flow. A preliminary study with acid ready dye (Ghadrati and Jury, 1990) showed some tonguing below the organic surface, but very little lateral spread into moist soil outside the projected edge of the treated area, even at 1 m depth. Dry soil shows no evidence of non-wetability. A laboratory column study of subsoil revealed a capillary fringe in which water content decreased from 33% (w/w) in the lowest 2 cm to 17% at 15 cm height, after 25 h drainage. Above 15 cm water content diminished to 13%. This pattern suggests the shallow depth above a plate surface at which most unsaturated flow would occur.

Data for several climate parameters, some of which have been measured over a period of 20 y, are collected every 20 s, integrated into 20 min intervals, and transmitted from Bikini Atoll via a GOES satellite (Gouveia et al., 2002). The November means (experiments were conducted in November) are shown in Table 1. Of all measured parameters, rainfall varies most. Annual rainfall for 19 y beginning in 1984 is listed in Table2 along with monthly mean rainfall. About 75% of total annual rainfall comes from June through November (Table 2). Rainfall is quite variable in both amount and frequency, and can be heavy during major storms.

A rectangular welded steel plate, 3.05 × 2.13 m (referred to as Lysimeter 1) was constructed as shown in Figure 1. It was inserted at 2–4% slope from the horizontal, rising from front to back and left to right, that is, with both tip and tilt. Lower edges at left and front had 7.62 cm-high rims, with a screened drain at the corner. A 15 cm-high I-beam was welded outside the front edge to hold the plate rigid when pushed, and the back edge was sharpened to shear roots. The plate was stiffened cross-wise with three pieces of channel iron welded to the plate bottom.

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[1]Stone and Robison, unpublished data

The lysimeter was installed between coconut (cocos *nucifera* L.) trees using a D-7 Caterpillar bulldozer, a Pettybone All-Terrain forklift with independent movement of the two fork limbs, and a large rubber-tired bucket loader. A 20 m trench was excavated 2 to 2.5 m deep, and ~3 m wide, with vertical sidewalls. A shorter length trench of the same depth and width was dug perpendicular to the midpoint of the longer trench forming a T-shaped excavation site that provided large machines access to the headwall of the long trench where the lysimeter was to be inserted.

The plate was supported by the forklift to intended slope (Figure 2 upper left) and pushed about 0.6 m into the vertical headwall one meter below the surface (Figure 2 middle left). The rubber-tired forklift lacked sufficient traction to fully insert the lysimeter. Without removing the forklift, a D-7 bulldozer was placed behind and in contact with the forklift, and a rubber-tired front-end loader was placed behind and in contact with the bulldozer (Figure 2 lower left). All machines started pushing slowly in unison to finish inserting the lysimeter (Fig. 2 upper right). This method worked extremely well maintaining desired slopes and excellent contact between the plate surface and soil.

A large rectangular or spherical collection chamber was placed in the trench below ground level about 1 to 1.5 m in front of the lysimeter plate with the top 0.6 m above the ground surface. A 7.6 cm PVC pipe was run from the lysimeter drain through an 8 cm hole cut in the chamber (Figure 2 middle right). Trenches were then backfilled with particular attention to consolidating soil against the collection chamber and trench-face where the plate was emplaced (Figure 2 lower right). The outflow pipe inside the collection chamber drained into a 23 L collection bottle with high and low water-level switches connected to an in-line peristaltic pump, a flow meter, and absorption columns to remove radionuclides of interest before exiting water was discharged. Twelve-volt batteries, charged by solar panels, were used to power the pump so the system could operate for long periods with only occasional replacement of batteries. Ladders were used to access the chamber to collect water and filters and to maintain equipment.

Lysimeter performance was determined by applying controlled quantities of water to a ground area that extended 15 cm beyond lysimeter dimensions to ensure coverage over the lysimeter. The area was watered alternately lengthwise and widthwise multiple times with a fan-shaped hose nozzle to produce, as much as possible, a uniform distribution of water. Saturated soil samples, collected from 15 cm depth increments to a depth of 1 m and

50 cm increments from 1 to 2 m, were oven dried to determine the maximum FWC of the coral soils as a function of depth. The same procedure was used to determine FWC of the soil at various times during the experiments.

### Evapotranspiration calculations

Coconut trees cover a large portion of Bikini Island (8.5 m grid spacing) with other types of trees scattered throughout. Understory vegetation consists of a variety of low-growing plants and grasses. Much of the soil surface is shielded from sunlight with some type of vegetation, either at height or at ground level, such that sunlight directly on soil is reduced.

The ET when FWC of coral soil is 50% or more is between 4 to 9 mm $d^{-1}$ based on pan-evaporation measurements (Clegg and Robison[2]). Average $ET_0$, defined as the evapotranspiration rate from a reference surface not short of water (FAO 56,1998), is listed as between 5 to 7 mm $d^{-1}$ for warm tropical humid conditions such as Bikini (FAO 56, 1998, Chapter 1, Table 2). A more rigorous analysis of atoll ET was made using Penman-Monteith methods (FAO 56, 1998; Smith et al., 1996; Allen et al., 1994 a, b) and climate data for November (Table 1). The basic equation for $ET_0$ is:

$$ET_0 = [0.048\ D\ (R_n - G) + g\ (900 / T + 273)\ U_2\ (e_s - e_a)] / D + g\ (1 + 0.34U_2) \quad [1].$$

- D(slope of vapor pressure) = 0.226, kPa $^0C^{-1}$ (FAO 56, 1998, Annex 2, Table 2.4).
- $R_n$ (net solar radiation) = 5.8 MJ $m^{-2}d^{-1}$ (our data and equation 39, chapter 3, FAO 56, 1998). $R_n = R_{ns} - R_{nl}$, and $R_{ns} = (1-a)R_s$ where a is the albedo (a = 0.25 for our situation). $R_s$ is the quantity we measure at the atoll. $R_{nl}$ is calculated with equation 39 in chapter 3 of FAO 56, 1998. Equation 39 contains a ratio $R_s/R_{so}$ where $R_{so}$ is the value of $R_s$ on a cloudless day. $ET_0$( or $ET_f$) do not change whether $R_s/R_{so}$= 1.0 for a cloudless day or 0.85 for a partially cloudy day.
- G (soil heat flux) = 0 $MJm^{-2}d^{-1}$ because monthly temperatures are essentially constant (FAO 56, 1998, Chapter 3 equation 43)
- g (psychometric constant) = 0.067 kPa $^0C^{-1}$ [FAO 56,1998, Annex 2, Table 2.2 (atoll elevation is 3 to 4 m)].
- T (mean daily air temperature) = 28.4 $^0C$ (Table1)
- $U_2$ (mean monthly wind speed) = 2.7 m $s^{-1}$ (Table 1)

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2 Clegg and Robison, 1983-1988 unpublished data

- $e_a$ = [1.431($RH_{max}$ )/100+ 2.564($RH_{min}$)/100]/ 2 and $e_s$ = [$e^0$($T_{max}$) + $e^0$($T_{min}$)]/2 , and $e^0$(T) = 0.6108*EXP[17.27xT/(T+237.3)].
- $RH_{max}$ (maximum relative humidity) = 95 % (Table 1)
- $RH_{min}$ (minimum relative humidity) = 74 %(Table 1)
- $e_a$ (actual vapor pressure) = 1.48 kPa (calculated with our data)
- $T_{max}$ (maximum air temperature) = 31.5 $^0$C (Table 1)
- $T_{min}$ (minimum air temperature) = 26.3 $^0$C (Table 1)
- $e_s$ (saturation vapor pressure) = 3.96 kPa (calculated with our data)

Substituting these values into Equation 1 gives $ET_0$ = 6.1 mm $d^{-1}$. When the adjustment factor $K_c$ = 0.9 for coconut palm groves (FAO 56,1998, Chapter 7, Table 17) is applied, the final estimated $ET_f$ = 5.5 mm $d^{-1}$ ($ET_f$ = $ET_0$*$K_c$).

## Results

**Experiment 1:** Lysimeter 1 was installed November 1997 when there was little prospect of rain. Thus, water totaling 1514 L was applied on the extended lysimeter area over a 2 h period. This is equivalent to 18.5 cm of water, or 1204 L over the 3.05 × 2.31 m lysimeter. The first flow rate measurement was 66 L $h^{-1}$. The flow-rate over 48 h is shown in Figure 3A. Decline in flow rate after break through occurred rather rapidly and flow was essentially complete in about 50 h. Water volume was measured for the 4.5 h period covered by the first six flow-rate data points. The last six flow-rate data points were fit with a fourth order polynomial (Figure 3B) that shows more detail at lower flow rates. The flow-rate curve was integrated (4.5 to 48 h) to determine the remaining water that would have been measured had the flow meter not malfunctioned.

Based on measurements in soil bordering the lysimeter, FWC was 25% above the lysimeter and soil was at 50% of field capacity at time of watering. Thus, 814 L of 1204 L applied, was required to saturate the soil. Total "collection" water from the lysimeter was 337 L (174 L of water actually collected and 163 L estimated by integrating the flow-rate curve in Figure 3B). The "collection" water, when added to the soil saturation water, totals 1151 L, leaving a deficit of 53 L [(applied water) - (soil-saturation water + collection water)]. The 53 L deficit is equivalent to an ET rate of 5.4 mm $d^{-1}$, which is consistent with the Penman-Montieth calculations. Thus, the LCE is very close to 100% based on these initial data and measurements of FWC.

**Experiment 2:** In November 1999 there was adequate rainfall to saturate soil and produce an outflow from Lysimeter 1 on 11/3. The flow rate was very low but rain occurred overnight and the first flow rate measurement of 2.7 L $h^{-1}$ was made on 11/4. An additional 1.27 cm of water was added to the lysimeter on 11/4, and each morning for 10 d thereafter. Flow rate reached steady cycling state as shown in Figure 4 beginning on day 5. The curve over the next 6 d shows how well steady state was established.

Total water applied over the lysimeter for 10 d beginning 11/4 was 131.3 mm or 852 L, of which 127 mm was from irrigation and 4.3 mm from rainfall. Water collected over 12.5 d beginning on 11/5 until flow stopped on 11/12 was 422 L. The difference is 430 L or 66 mm for 12.5 d that translates to an ET rate of 5.3 mm $d^{-1}$. Again this is consistent with the Penman-Monteith calculation and a nearly 100% efficient lysimeter.

## Discussion

A very large plate lysimeter (3.05 × 2.29 meters) installed at Bikini Island has proven to be a very efficient water collecting system unlike some reports where small plates were used. Large dimensions of the lysimeter overcome most water tension border effects associated with small plate lysimeters and in turn lead to a very high LCE. However, it does require heavy-duty equipment to install such large plates in a manner that does not disturb the overlying column of soil. Since installation of lysimeter 1, seven stainless steel lysimeters have been installed, four 2.13 × 1.52 m and three 3.05 × 2.29 m. Stainless steel was used so plutonium (Pu) concentration also could be measured. Some of these lysimeters were modified to include drains in both corners for water collection thereby eliminating tilting of lysimeters left or right at time of insertion. In some cases two lysimeters were placed within about 6 m of each other and a collection chamber was placed midway between them. Drain outlet pipes of both lysimeters were run to the same collection chamber but separate collection jugs. Efficiencies of these lysimeters have not been determined as was Lysimeter 1 because collecting water to determine the concentration of radionuclides being transported to groundwater is our primary interest. However, they all discharge large volumes of water during periods of rainfall adequate to produce recharge of the lens. Comparative collected volumes during recharge conditions indicate that all of them are highly efficient in a manner similar to lysimeter 1.

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Table 1 November climate measurements at Bikini Atoll†

| Parameter | Value |
|---|---|
| Mean daily wind speed, m $s^{-1}$ | 2.6 ± 0.17 |
| Daily low relative humidity, % | 74 ± 4.8 |
| Daily high relative humidity, % | 95 ± 5.5 |
| Daily mean relative humidity, % | 81 ± 4.1 |
| Daily low air temperature, $^{0}$C | 26.3 ± 0.90 |
| Daily high air temperature, $^{0}$C | 31.5 ± 1.1 |
| Daily mean air temperature, $^{0}$C | 28.4 ± 0.47 |
| Daily insolation ($R_s$), MJ $m^{-2}$ $d^{-1}$ | 15.8 ± 3.5 |

† Average ± 1 std. dev. of 3 stations for November 2001 and 2002

Table 2. Annual and Monthly Rainfall at Bikini Atoll

**1984 through 2003**

| **Year** | **cm** | **Month** | **cm** | **Std. Error** |
|---|---|---|---|---|
| 1984 | 79.5 | January | 5.08 | 1.17 |
| 1985 | 126 | February | 3.56 | 0.635 |
| 1986 | 207 | March | 7.11 | 2.08 |
| 1987 | 110 | April | 6.10 | 1.14 |
| 1988 | 127 | May | 7.87 | 2.01 |
| 1989 | 183 | June | 12.4 | 1.98 |
| 1990 | 249 | July | 16.5 | 2.16 |
| 1991 | 177 | August | 20.8 | 2.54 |
| 1992 | 149 | September | 24.4 | 2.67 |
| 1993 | 149 | October | 20.1 | 2.34 |
| 1994 | 162 | November | 21.6 | 3.02 |
| 1995 | 147 | December | 9.14 | 1.22 |
| 1996 | 187 | | | |
| 1997 | 242 | | | |
| 1998 | 110 | | | |
| 1999 | 100 | | | |
| 2000 | 132 | | | |
| 2001 | | | | |
| 2002 | | | | |
| 2003 | | | | |

Figure Legends

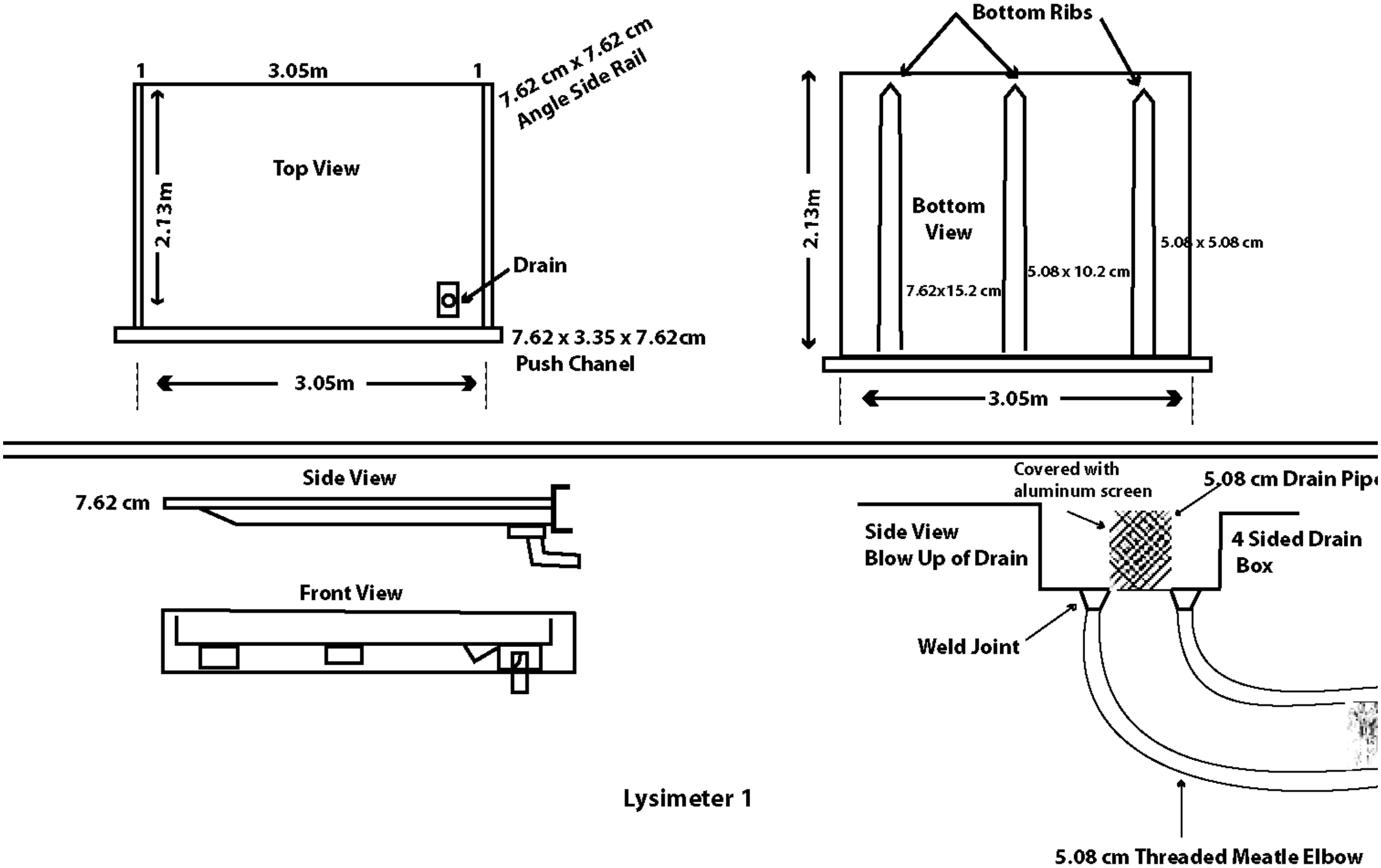
Figure 1. Design of large plate lysimeter 1. Drains for subsequent lysimeters were moved to the very corner of the plate.

Figure 2. This series of pictures shows installation of the lysimeter. Desired slope is established with the forklift (top left). The middle left photo shows initial insertion of the plate. The bottom left photo shows the plate fully inserted into the headwall. The dark line about head high on the workers is the plates heavy-duty push channel (see Figure 1). The top right photo shows the forklift, bulldozer, and front-end loader lined up in tandem that fully inserted the plate. The middle right photo shows the lysimeter outlet being plumbed into the collection chamber (in this case a cylindrical tank). The lower right picture shows the finished site after backfilling. The lysimter is located under the area marked by the 4 flags. The top of the collection chamber is visible in the middle of the white-sand backfill area.

Figure 3a. Flow rate from time zero to 4.5 h after 184.4 mm of water was applied to the ground surface over the lysimeter.

Figure 3b. Flow rate from 4.5 h to 44.4 h after water was applied. Flow-rate data were fit with a polynomial curve that was integrated to determine the total volume of water- output over that time.

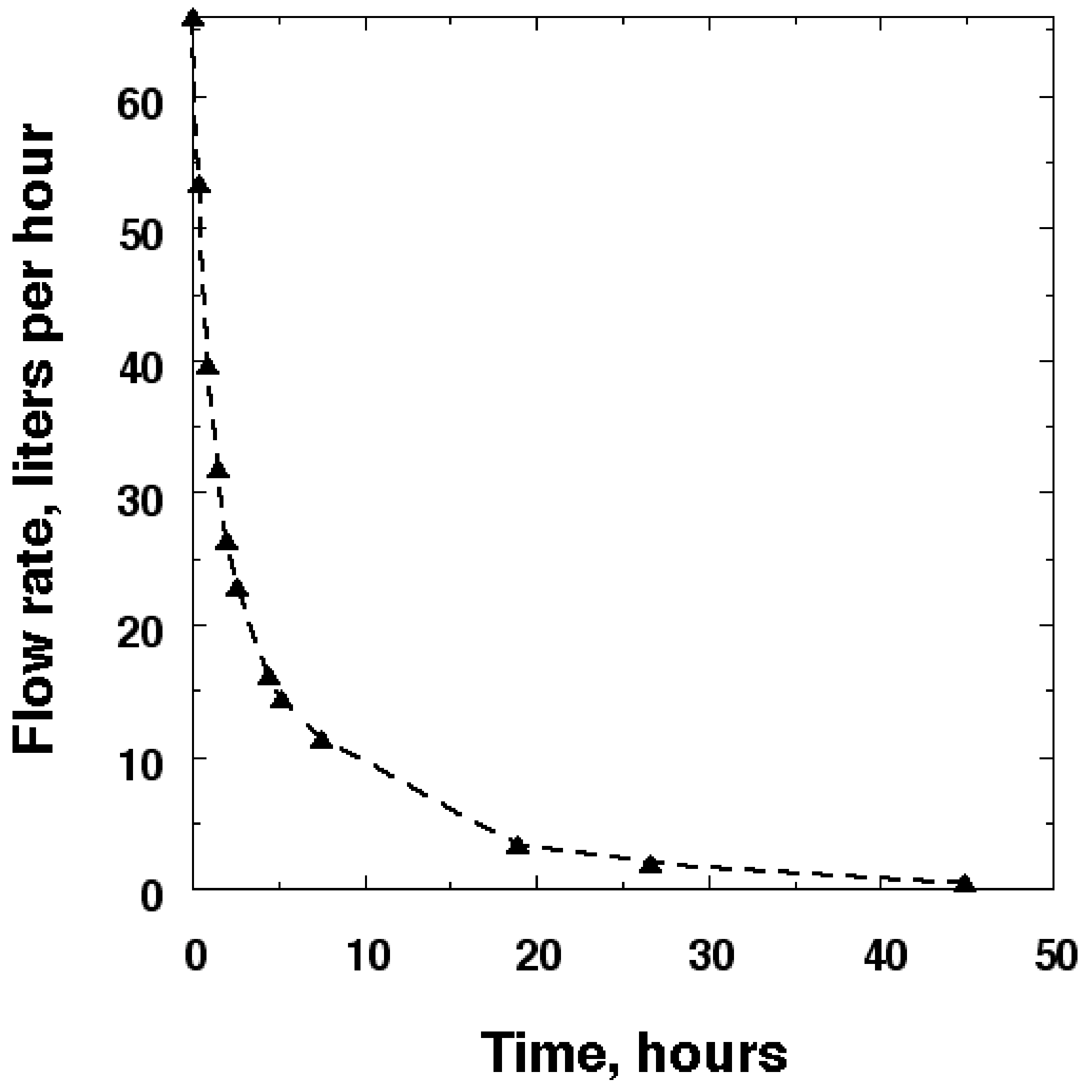
Figure 4. Flow rate from lysimeter 1 over a 12-d period. Daily rainfall (mm) is listed between the arrows. Arrows indicate application of 12.7 mm of water over the lysimeter.

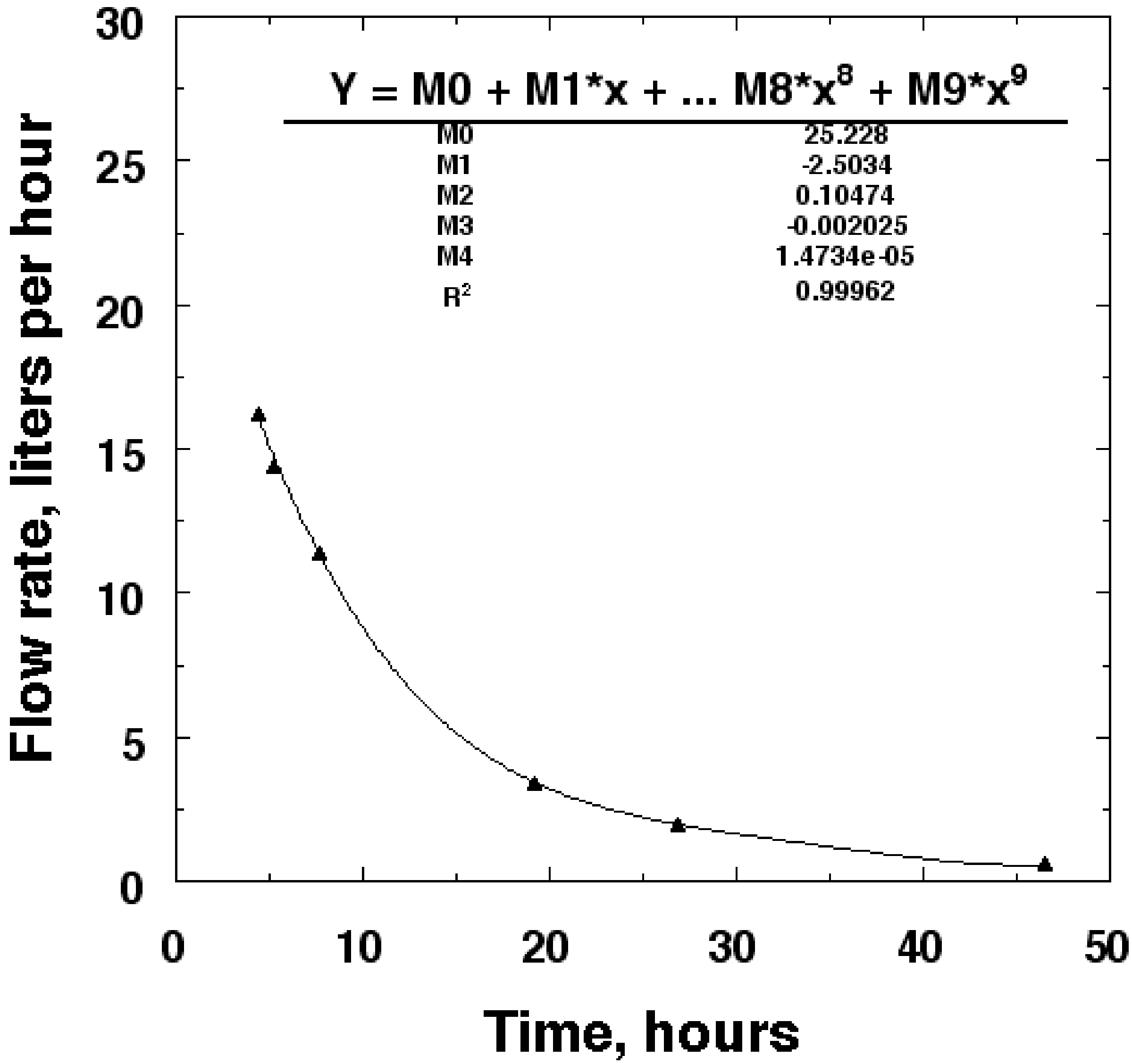

1
3.05m
1
7.62 cm x 7.62 cm
Angle Side Rail
Top View
2.13m
Drain
7.62 x 3.35 x 7.62cm
Push Chanel
3.05m
Bottom Ribs
2.13m
Bottom
View
5.08 x 5.08 cm
5.08 x 10.2 cm
7.62x15.2 cm
3.05m
Side View
7.62 cm
Front View
Covered with
aluminum screen
5.08 cm Drain Pip
Side View
Blow Up of Drain
4 Sided Drain
Box
Weld Joint
5.08 cm Threaded Meatle Elbow

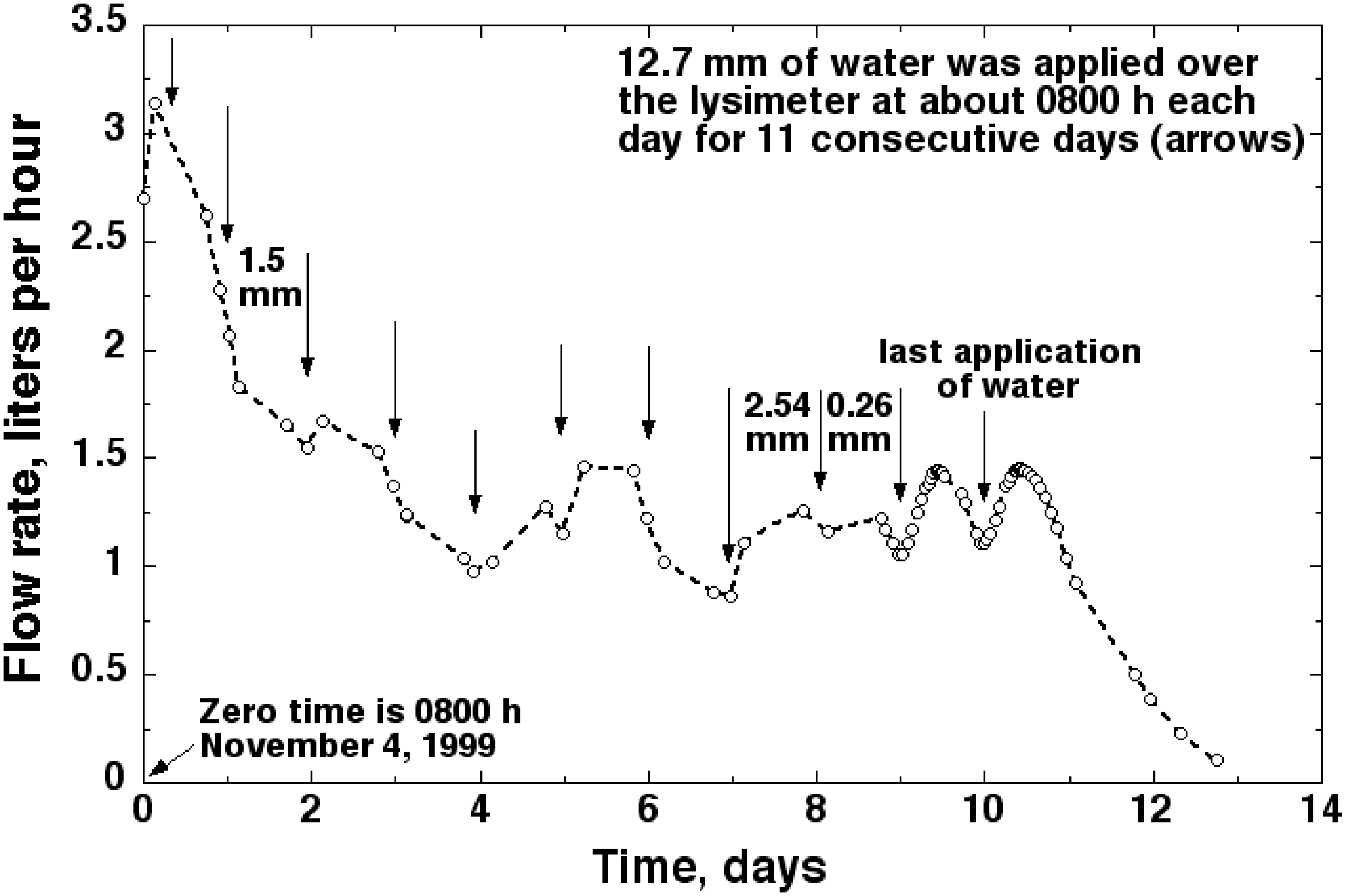
Lysimeter 1







Flow rate, liters per hour
60
50
40
30
20
10
0
0
10
20
30
40
50
Time, hours


Y = M0 + M1*x + ... M8*x8 + M9*x9
M0 25.228
M1 -2.5034
M2 0.10474
M3 -0.002025
M4 1.4734e-05
R2 0.99962
Flow rate, liters per hour
Time, hours
0
5
10
15
20
25
30
0
10
20
30
40
50



12.7 mm of water was applied over the lysimeter at about 0800 h each day for 11 consecutive days (arrows)
1.5 mm
2.54 mm
0.26 mm
last application of water
Zero time is 0800 h November 4, 1999
Flow rate, liters per hour
Time, days
0
0.5
1
1.5
2
2.5
3
3.5
0
2
4
6
8
10
12
14